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NASA Contractor Report 3305

Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport - Project Plan

Staff of Boeing Commercial Airplane Company

CONTRACTS NAS1-14742 and NAS1-15325
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Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport - Project Plan

Staff of Boeing Commercial Airplane Company
Boeing Commercial Airplane Company
Seattle, Washington

Prepared for
Langley Research Center
under Contracts NAS1-14742 and NAS1-15325

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FOREWORD

This document constitutes the plan for the IAAC Project to be accomplished under Contracts NAS1-14742 and NAS1-15325. The plan was originally published and submitted to NASA as a Boeing Commercial Airplane Company Document. It has been updated and is being published as a NASA CR to facilitate its use as a reference document.

Preparation of this plan was initiated under Contract NAS1-14742 and was completed under Contract NAS1-15325. NASA technical monitors for this task were D. B. Middleton and R. V. Hood of the Energy Efficient Transport Program office at Langley Research Center.

The work was accomplished within the Preliminary Design Department of the Vice President–Engineering organization of the Boeing Commercial Airplane Company. Key contractor personnel who contributed were:

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Principal measurements and calculations used during this study were in customary units.

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1.0 SUMMARY

This report reflects results of a contractor study to establish a recommended plan for Active Controls Technology (ACT) development to the point that commercial transport design could be committed to the full incorporation of ACT. Such transport designs would rely on flight-critical systems that provide ACT functions to maintain adequate structural integrity and control of flight. Before the airframe and operating airline industries and the regulatory agencies will be receptive to commercial transport designs that are truly dependent upon ACT systems, three important questions must be answered:

1. When implemented to the fullest extent during preliminary design of a practical transport, does ACT offer sufficient benefit potential to warrant its development to a "ready for commitment" status?

2. If the benefit potential, defined in answer to the first question, is sufficiently attractive, what methods and laboratory and flight evaluation developments are required to bring ACT to commitment readiness status?

3. After adequate development, are system reliability and maintainability characteristics technically and economically acceptable?

The recommended plan, which addresses these questions, consists of three major elements:

1. Configuration/ACT-System Design and Evaluation

   The configuration element would provide a credible assessment of ACT benefits and define related development requirements in response to the first two questions noted above. It is recommended that this element be pursued, using state-of-the-art implementation of the ACT control systems, so that the benefit assessment does not depend on technical breakthroughs.

   It is further recommended that this element be pursued by a team of technical specialists representing the disciplines that would ultimately verify the benefit assessment and implement the required development. Approximately 30 months would be required to complete this element.

2. Advanced Technology ACT Control System

   This element would identify state-of-the-art technology advancements appropriate to optimized implementation of ACT system functions and integration of ACT with guidance and control systems avionics. It is recommended that this element be pursued in parallel with the configuration element, so that the final benefit evaluation would include a study of the advantages of technology advancement predictions. Depending upon the duration and depth of the overall system evaluation, approximately 40 months would be required to complete this element.

3. Test and Evaluation

   This element would be devoted to laboratory and flight verification of ACT systems development to provide a positive answer to the final question noted

above. It would be pursued only if a sufficiently positive potential benefit resulted from the assessment effort described for the configuration element. Test and evaluation would pursue both state-of-the-art system integration defined in the configuration element and technology advancements and integration with guidance and control functions investigated during conduct of the advanced technology element. Depending upon the extent of the required flight evaluation (which cannot be established positively at this time), test and evaluation would take at least 3 years.

The program plan, resulting from the study, is directed toward answering basic questions regarding ACT, identifying high-risk areas that now prevent exploitation of the potential benefits, and accomplishing selected test and evaluation work. The plan recognizes and builds upon many accomplishments resulting from related NASA and U.S. Air Force programs. Although the funding identified for the NASA Energy Efficient Transport (EET) Programs will significantly contribute to the expected needs of the recommended programs, the study indicated that those funds probably would not be adequate to ensure production commitment readiness, particularly if extensive flight evaluation is required.

2.0 INTRODUCTION

2.1 BACKGROUND

An Aircraft Energy Efficiency (ACEE) Program has been established within NASA to develop advanced technology that will result in more efficient use of energy by transport aircraft. One element, the Energy Efficient Transport (EET) Program, is specifically directed toward this goal through improvements to the airframe. The objective of EET is to expedite the application of active controls and advanced aerodynamics that provide the potential for development of commercial transport fleet aircraft capable of greater fuel efficiency and more economic operation.

Active Controls Technology (ACT) is a design concept to improve airplane performance by relying upon the flight control system to augment the airplane's stability and reduce aerodynamic drag, while reducing structural weight requirements. Performance benefits are derived from improved aerodynamic efficiency and reduced airplane weight. Airplane stability is augmented to allow a smaller empennage and aft center of gravity, resulting in reduced trim drag structural weight. Structural weight is also reduced by activating control surfaces to reduce maneuvering and gust loads, to reduce fatigue loads due to turbulence, and to damp structural modes that contribute to flutter instability.

Extensive research and testing in these technologies have been carried out through independent NASA- and industry-sponsored programs. These programs are further detailed in Appendix A. Results are encouraging, showing potential performance improvements and demonstrating the working elements of various active controls systems. Figure 1 shows that commercial operational experience exists on only two aspects of ACT; augmented stability and ride control. These applications are not integrated, but, typically, have been individually designed and implemented. A significant body of evidence strongly suggests that an integrated application of ACT will yield the most significant performance improvement. In addition, major ACT applications will yield reductions in airframe weight, with subsequent reductions in stiffness. Thus, the various ACT functions cannot be considered independently, but must be designed in concert to preserve acceptable airplane characteristics. This has not been accomplished to date, even in research activities.

Recent advances in solid-state electronics promise increasing critical system reliability and cost reductions. However, little effort has been expended toward clear identification of overall benefits, cost of ownership, and technical risks associated with a far-term major application of ACT.

To meet the EET Program objective of expediting the application of ACT to commercial transports, the factors currently impeding such application must be identified, and a plan to reduce or eliminate them must be developed; this study was undertaken to accomplish this.

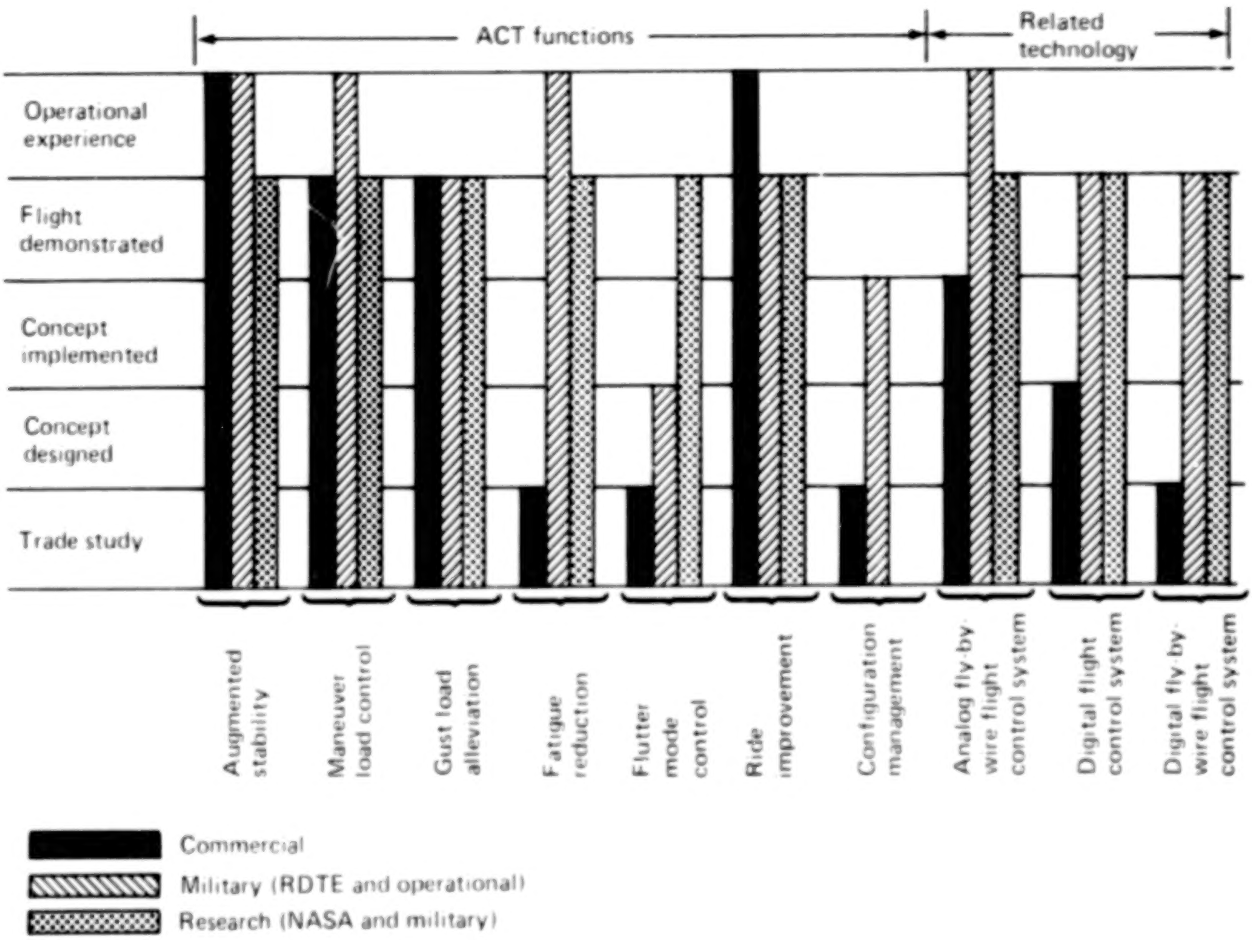

Figure 1. Active Control Technology State-of-the-Art

2.2 STUDY OBJECTIVE

The study objective was to develop a comprehensive overview of the work required to bring Active Controls Technology to a state of readiness for incorporation on a new generation of commercial transport aircraft and to identify those elements of research and development work that should be undertaken immediately. For such an application, it is necessary that predicted performance benefits be credible, that the predicted cost of ownership be acceptable, and that the technical and economic risks be comparable to those accepted in new commercial airplane programs.

The result of this study is a recommended program for development of ACT for commercial transport application (sec 3). Development, as used in this sense, means determining the benefit, assessing the risk, and implementing experiments designed to reduce the risks to a commercially acceptable level.

The purpose of this program is to remove existing deterrents to a major commercial application of ACT. A number of ACT design studies have been applied to various airplane missions, but, with few exceptions, results of these studies lack credibility. The first objective of this recommended program is to produce a credible, indepth assessment of the benefit associated with a major ACT application to a commercial transport. This assessment will be based upon major far-term development of a new airplane, as opposed to addition of ACT to an existing airplane to produce a derivative. A discussion of the commercial transport mission that would have the greatest potential for fleet fuel reduction through use of ACT and a probable ACT configuration is in Appendix B of this report.

Maximum benefit of ACT will be achieved when the flight vehicle configuration is influenced by the use of all beneficial ACT functions. Some of these functions will likely be incorporated as flight-critical systems. A major obstacle to such a broad application of active controls is the perceived risk of relying upon such control systems. Management of commercial airframe manufacturers and airlines, as well as part of the technical community, are aware of the risk, which stems from recognition that major beneficial application of ACT probably will rely upon flight-critical systems. Thus, the second objective of the recommended program is to identify the risk areas.

Significant reduction in the identified risk areas will only result from "hands-on" experience with ACT systems. The third objective of the recommended program is to reduce the risks associated with the use of ACT through test and evaluation. Risk reduction will be accomplished, to the degree possible within funding limitations, to a level commensurate with commercial practice.

2.3 STUDY APPROACH

Successful application of ACT in the design of a commercial transport will involve essentially all technical disciplines of airplane design and will require courageous decisions by airplane manufacturer upper management. The approach to this study was to involve these people in the plan development.

ACT requires fresh approaches to airplane design, especially in structures and flight controls disciplines. Boeing upper management technical decision makers were continually involved in the plan development, and a group of experienced technical specialists

drafted and revised the plan. The overall plan and estimated resources were presented to all management levels of the Vice President of Engineering organization of the Boeing Commercial Airplane Company for their review and approval.

The planning effort began with the identification of specific objectives: benefit assessment, risk identification, and risk reduction. Major elements required to accomplish these objectives were influenced by resources and calendar time.

Each of the major elements was developed in detail consistent with its time position in the plan—the early elements in considerable detail, later ones in less detail. As the technical work progresses, information developed in early elements will influence the specifics of subsequent elements. The result of this planning effort is described in Section 3.0.

3.0 RECOMMENDED ACT PROGRAM

This section summarizes the program that the Boeing Commercial Airplane Company recommends NASA undertake as part of the Energy Efficient Transport Program. This recommended program contains several elements that should be started as soon as funding is available to provide results on schedule. The following discussion considers recommended program element priorities and summarizes objectives and timing of these elements.

3.1 PRIORITIES

The most pressing requirement is a credible assessment of the potential benefit from an integrated application of ACT to a commercial transport. As the highest priority element of the recommended program, this assessment should begin immediately. A key to practical implementation of ACT is the control system technology necessary to provide an ACT airplane with appropriate reliability (safety and dispatch). Because control system technology is fundamental to this concept, it is recommended that advances applicable to an ACT system implementation be investigated in parallel with the configuration design and evaluation aspect.

As the benefit assessment nears completion, the test and evaluation phase should be started to provide validation for the configuration aerodynamics and selected ACT system concepts and critical hardware. It is premature at this time to identify the flight-test phases that should be undertaken. Depending upon analysis and testing results, it may be necessary to flight test certain elements or aspects of an ACT airplane. Such necessary testing then should be considered.

3.2 OVERVIEW

The recommended ACT program has three major objectives, which are designed to remove or reduce the principal deterrents to major commercial ACT application. The first objective is to produce, for the first time, an indepth assessment of the benefit associated with major application of ACT to commercial transport during the design process, as opposed to an add-on application of ACT. There have been numerous studies of ACT applied to commercial transport missions. Typically, these studies have not included sufficient design and analysis detail to yield a believable determination of the associated performance and economic benefit.

The second major objective of the program is to identify the risks associated with the use of ACT. One important consideration, in this instance, is the viewpoint of managers responsible for the design decisions that would include or exclude ACT in the development of a commercial airplane. Another consideration is the reliability/availability necessary for a successful major application of ACT in a commercial airplane and the development of an ACT system implementation that meets these requirements.

The third objective, reduction of the identified risks to a level commensurate with commercial practice, will be addressed through careful detailed analysis in some instances, while others may require a confidence-building laboratory or flight-test demonstration. The program described in the following material will identify technical risk areas and begin the reduction of those risks through appropriate laboratory and/or flight test and evaluation.

The program consists of three major elements, as shown in Figure 2 and expanded in Figure 3. The first of these elements, Configuration/ACT-System Design and Evaluation, has the principal objective of producing a benefit assessment. This assessment will result from the design of an ACT transport. Careful attention will be given to the means of implementing ACT functions, the effect of the structural design and analysis attributable to ACT, and the cost of owning the resultant airplane and systems. The ACT system implementation associated with this part of the program will be a relatively low-technical-risk approach based on current technology system elements.

The second major element of the recommended program, Advanced Technology ACT Control System Definition, has as an objective the identification of advanced technology and/or methodology appropriate to the design and implementation of the ACT functions. The task will consider hardware components and synthesis methodology applicable to a 1990 time period. This element of the program will consider advanced technology and its effect on the cost of owning these ACT functions.

The objective of the third major element of the recommended program, Test and Evaluation, is intended to increase confidence in the overall benefit assessment and implementation risk through appropriate wind tunnel tests, piloted simulations, and acquisition and test of certain ACT system elements. The test and evaluation phase, as proposed in this recommended program, does include flight test, although the specific degree required is not currently identified. Consequently, required hardware system elements will be designed to be flightworthy for subsequent flight-test use. There is sufficient confidence that the benefit of ACT in a commercial environment will be so positive as to permit start of the ACT system advanced technology work in parallel with the benefit assessment. However, major cost items of the test and evaluation phase should be delayed until there is further evidence of the benefit assessment outcome.

The three major elements of the proposed program are discussed in more detail in Sections 3.3, 3.4, and 3.5.

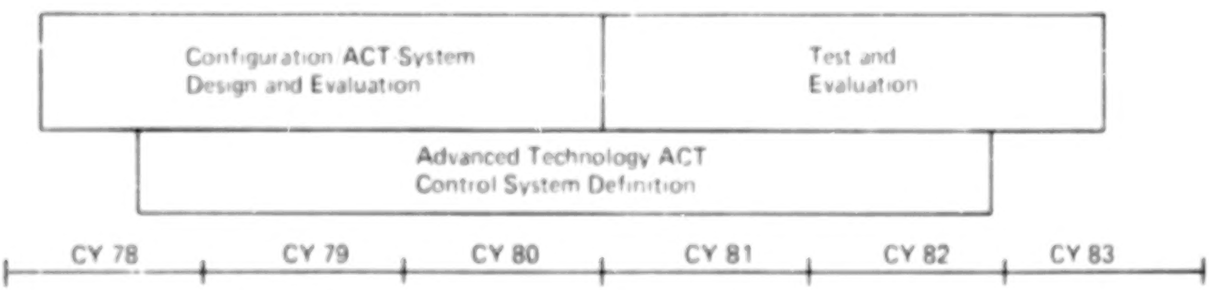

Figure 2. Recommended ACT Development Program, Major Elements

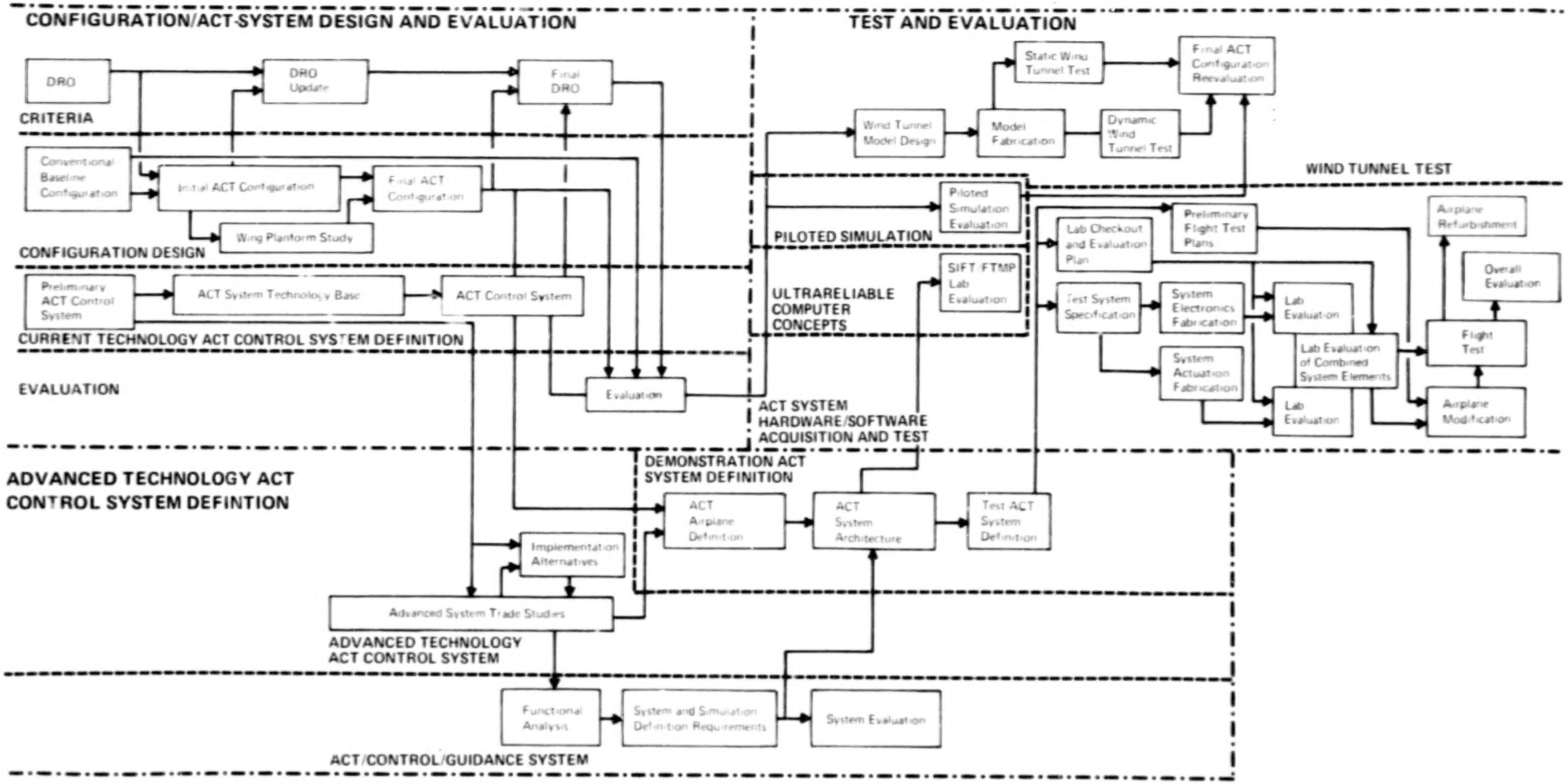

Figure 3. Recommended ACT Development Program

3.3 CONFIGURATION/ACT-SYSTEM DESIGN AND EVALUATION

The configuration element of the recommended program is designed to result in assessment of the benefit of ACT to commercial airplane design (fig. 3) and consists of:

- Determination of criteria to which the configuration will be designed
- Design of the ACT Configuration
- Determination of the ACT control system upon which the configuration will depend
- Evaluation, considering performance, economics, and technology

Measuring the effect of the technology change on performance and economics of an airplane, without building the airplane, will require careful attention to changes that are introduced, as well as a reference airplane for which similar economic performance calculations have been made.

3.3.1 CRITERIA

At the outset of a commercial airplane design program, a document or set of documents is created and designated as design requirements and objectives (DRO). This statement of the target to which the airplane will be designed obviously influences the resulting configuration; therefore, the DRO must be defined early in the program. The recommended approach is to prepare a preliminary DRO at the outset of this program and then update it as the program proceeds. The initial document will highlight those elements of the DRO that are affected by ACT and, as a consequence, differ from the reference airplane DRO. As the design of the ACT configuration progresses, the DRO document will be updated, based upon the knowledge gained. Toward the end of this program element, the final update will produce a consistent DRO and Final ACT Configuration.

3.3.2 CONFIGURATION DESIGN

The initial step of the configuration element is selection and understanding of the reference Conventional Baseline Configuration (fig. 4). This airplane is the foundation for all of the configuration work. Considerations in the selection of the reference airplane will include availability of a good data base and the amount of fuel used in the market segment for which it was designed. The benefit of ACT is extremely configuration-sensitive; therefore, there may be configurations for which there is little or no benefit. Critical elements in the design of the reference airplane must be understood. The selected configuration will be a modern state-of-the-art transport with powered controls to prevent introduction of a spurious effect. Reference airplane technology will form the technology base for the active controls airplane in all respects except ACT.

Following the reference airplane selection, the first ACT configuration (Initial ACT Configuration in fig. 4) will be developed. This configuration is an application of ACT, limited by constraining the wing planform to that of the reference airplane. The resultant design establishes one data point in the set required to determine where the configuration optimizes with ACT. This task also provides an opportunity to develop

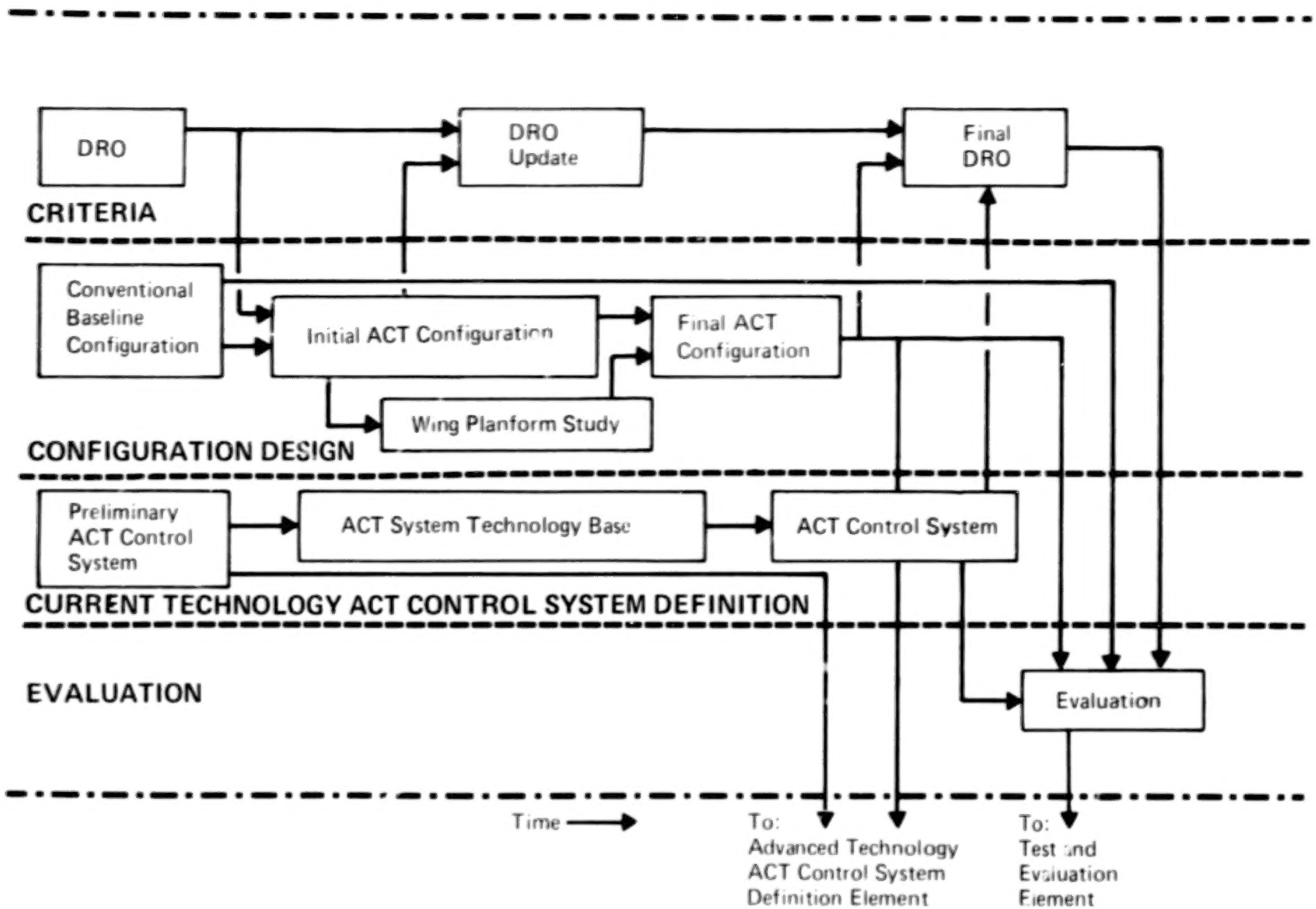

Figure 4. Configuration/ACT-System Design and Evaluation Element

and refine the analysis process to be used throughout the program. All potentially beneficial ACT functions are included in the design, regardless of current limitations on implementation technology.

The third step in the configuration element is the examination of a number of wing planforms (Wing Planform Study in fig. 4) to determine how ACT most favorably affects design of the subsonic transport. The recommended approach is to consider several aspect ratios, with thickness and sweep chosen to provide a constant cruise Mach number, and then select and design several wings using ACT wherever it is beneficial. These additional wings will provide data from which a near-optimum wing planform can be chosen.

The Final ACT Configuration (fig. 4) will then be selected, based upon results of the Initial ACT Configuration and wing optimization subtasks. To allow comparison, this final configuration will be designed and sized to meet the mission associated with the reference airplane, and performance will be calculated similarly to that used for the reference airplane.

3.3.3 CURRENT TECHNOLOGY ACT CONTROL SYSTEM DEFINITION

The previously described configuration design proceeds under the assumption that any ACT functions that were beneficial to the configuration could be implemented in a satisfactory manner. The objective of this portion of the recommended program is to determine a high-confidence means of implementing the beneficial ACT functions, using current technology. The work will begin with preliminary system definition (Preliminary ACT Control System in fig. 4), which is used to provide weight and volume requirements for the system used in the configuration design. The first major step will be to develop a technology base (ACT System Technology Base, fig. 4) from which the system definition can be derived. The recommended approach in the development of this technology base is to explore two extremes of implementation architecture. The first of these will integrate appropriate ACT functions into common computing elements and then will examine the redundancy required to provide necessary availability and reliability. Certain ACT functions are conceivably best suited to a segregated implementation. The second major part of the technology base development will examine such implementations. The final step will define the ACT system (ACT Control System in fig. 4) that would provide the beneficial functions and, therefore, be included in the Final ACT Configuration. Appropriate reliablity and cost-of-ownership analyses will be performed on this system.

3.3.4 EVALUATION

The final step in the configuration element of the recommended program is to compare the performance of the Final ACT Configuration to that of the reference airplane, considering associated cost of ownership, overall airplane economics, and related technical risks. Recognition of the ownership cost of the associated ACT system is an important part of the evaluation, because even the most technically interesting concept is not likely to be included in a commercial venture unless there is a favorable cost-benefit ratio. Another important aspect of the evaluation is recognition of any significant weaknesses in the preceding analysis, including recommendations for subsequent test and/or analyses to reduce the technical risk associated with ACT if the cost-benefit ratio is favorable.

3.4 ADVANCED TECHNOLOGY ACT CONTROL SYSTEM DEFINITION

The configuration design activity previously described is structured on the premise that ACT system implementation is low-risk and uses current technology. This approach is felt to yield the most credible assessment of the benefit of including ACT in the configuration design. There are two possible flaws in this line of reasoning: one, it may not be possible to provide a critical function with appropriate availability and/or reliablity through use of current technology, and two, the cost of ownership associated with the current-technology system implementation may be unacceptably high. These concerns established the requirement that this part of the recommended program (fig. 5) begin before the benefit assessment is completed. In addition, it is important that the relationship of the ACT systems to the control and navigation/guidance systems be understood and integrated where appropriate. This advanced technology element of the recommended program has three parts; Advanced Technology ACT Control System, ACT/Control/Guidance System, and Demonstration ACT System Definition.

3.4.1 ADVANCED TECHNOLOGY ACT CONTROL SYSTEM

The objective of the advanced technology element of the recommended program is to provide alternative means of implementing the ACT functions. This is accomplished by examining hardware implementation alternatives (Implementation Alternatives, fig. 5) for selected elements of an ACT system; e.g., sensors, data communications, computation, actuation, mode control, and caution/warning technology. This examination will be made to determine technology applicable to a 1990 airplane. Hardware elements judged suitable would then be included in the definition of an advanced system that provides the same ACT functions as the Current Technology ACT System for determination of comparative system performance reliability and economic data. The Advanced System Trade Study (fig. 5) includes consideration of advanced control law synthesis and digital implementation methods necessary to achieve the stated objective. The synthesis of ACT functions for a large commercial transport is technically difficult, and success of the ACT flight control applications, in part, will depend upon the ability to successfully produce such multiloop control laws. This task will explore control law synthesis methods and control system hardware effects on the ACT function performance.

3.4.2 ACT/CONTROL/GUIDANCE SYSTEM

This portion of the recommended program addresses the effect on the cockpit of introducing an additional complex control system in the advanced technology context previously described. During the first task in this effort (Functional Analysis in fig. 5), operational and performance objectives, considering the total avionics and flight control system, will be identified, and the information flow and processing required to accomplish those objectives will be analyzed. This functional analysis will begin with the creation of a mini-DRO for operation of the airplane and its subsystems most directly concerned with control of attitude, flightpath, and energy. The task continues with a review of the information flow requirements, considering active controls, autopilot, autothrottle, augmentation systems, navigation and guidance, propulsion control, instruments and displays, communication, and caution and warning. Results of this task will be separation of the required functions into elements of sensors, computation, actuation, and display. Functional breakdown of the flight control system, both conventional and active controls, will include emphasis on flight criticality.

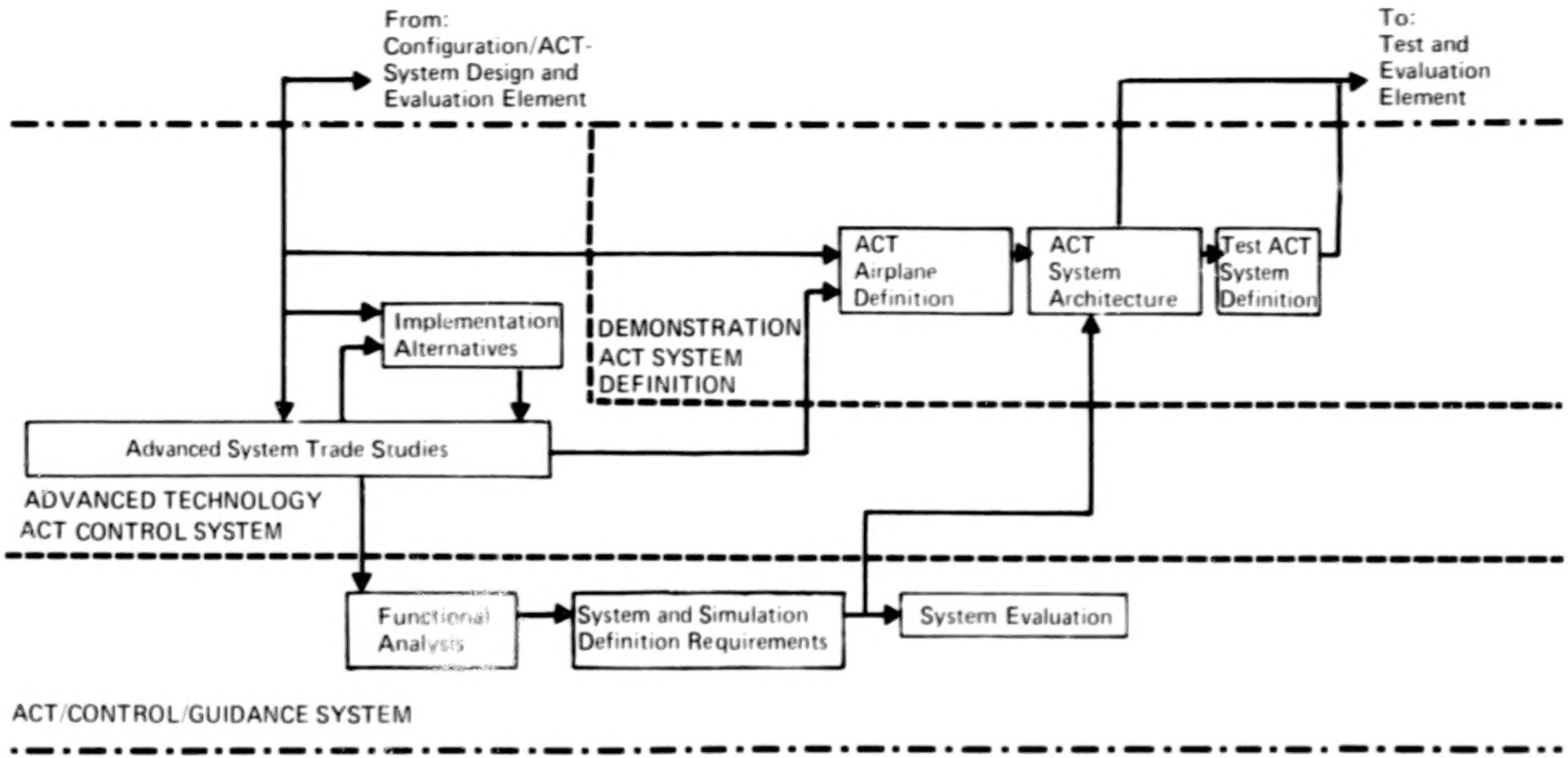

Figure 5. Advanced Technology ACT Control System Definition Element

The next task (System and Simulation Requirements Definition in fig. 5) consists of definition of an operational concept for this combined ACT/Control/Guidance System that meets the operational requirements and objectives determined in the function analysis. System definition will begin with development of an operational concept and a description of its use, including modes of operation, hierarchy of modes, and functional requirements. This will be followed by the definition of algorithm requirements for a piloted simulation. The algorithm development focuses on the function, rather than on a specific form of implementation that might appear in the airplane. In addition, flight-deck hardware requirements necessary to accomplish the subsequent piloted simulation are identified.

The purpose of the next task (System Evaluation in fig. 5) is to provide a piloted-simulation assessment of an aircraft system operational design that includes ACT elements. The evaluation will determine the impact of ACT on the airplane operation. Particular attention will be given to the relationships between system design and crew roles and procedures. The simulation evaluation will determine the utility of various system control and display combinations in management of the ACT airplane, rather than simply investigate handling qualities. Qualified jet transport pilots will be included in the study team.

3.4.3 DEMONSTRATION ACT SYSTEM DEFINITION

The final portion of the advanced technology element is identification of a potential demonstration ACT system as the basis for much of the work of the test and evaluation element of the recommended plan. The task begins with selection of the ACT airplane (ACT Airplane Definition in fig. 5) based upon the preceding configuration design work. The definition will include all potentially beneficial ACT functions, as well as function criticality, required reliability, primary control system, aerodynamic surfaces, and related airplane systems.

The next task (ACT System Architecture in fig. 5), will review the systems developed under the Current Technology ACT Control System Definition Task and the Advanced Technology ACT Control System Definition Task. Following this review, a control system that meets requirements of the ACT Airplane (defined above) and that is suitable for flight testing in the time frame of the Test and Evaluation element, will be established.

The final task is the Test ACT System Definition (fig. 5), in which elements of the ACT system that should be tested will be determined and test objectives will be established.

3.5 TEST AND EVALUATION

Testing will be required to provide reduction of the perceived risk associated with the use of Active Controls Technology. The configuration design study previously described depends upon limited wind tunnel tests and very limited control system laboratory work. Assuming that all indications point to a favorable benefit assessment, major test and evaluation will start near the end of the evaluation element activity. The timing of these activities is approximately 2½ years following program start; consequently, they cannot be described in detail. Specific test requirements and objectives will be a result of preceding analyses; Figure 6 illustrates the components of the test element.

3.5.1 WIND TUNNEL TESTS

Assuming that the benefit of ACT is sufficiently favorable, wind tunnel test planning, model design, and fabrication (fig. 6) could be started near the end of the Final ACT Configuration design task. This testing would be to substantiate the Final ACT Configuration, and would include static force and pressure models and probably dynamic wind tunnel models for flutter tests. If unique controls have been included in the Final ACT Configuration, specific large-scale model segments or high Reynolds number tests may be required. Results of these tests then will be used to refine the design and reevaluate previously determined benefits. This work would best be accomplished under independent research and development funding.

3.5.2 PILOTED SIMULATION

One approach to active controls design is to make the active controls functions as nearly transparent as possible from the pilot's view point. With this approach, it will be difficult for the pilot to tell whether he is flying an airplane where active controls are altering the basic characteristics, or whether he is operating an unaugmented airplane. In any event, acceptable handling qualities are necessary when the various active controls functions are engaged. Therefore, as part of the test and evaluation element in the recommended program, a major simulation task (piloted simulation evaluation in fig. 6) probably will be required. The evaluation would include examination of failed and partially failed active controls functions, as well as normal operation.

3.5.3 ULTRARELIABLE COMPUTER CONCEPTS

NASA is sponsoring development of multiprocesser, ultrareliable computing concepts, referred to as software implemented fault tolerance (SIFT) and fault tolerant multiprocessers (FTMP). Digital implementation of active controls functions may benefit from such concepts. The ACT configuration design and benefit determination does not depend upon these concepts, but they may carry the potential of reducing ACT system ownership cost. A careful review should be made of these concepts to determine their potential when applied to an active controls airplane. Depending upon results of the previously described analyses and tests and the state of readiness of SIFT/FTMP hardware, it may be appropriate to conduct a laboratory evaluation of one or both of these concepts (SIFT/FTMP Lab Evaluation, fig. 6). To exercise all their potential capability would be a major undertaking. Applying the required resources to accomplish this undertaking will be carefully weighed against applying those same resources to other parts of the test and evaluation element of this recommended program.

3.5.4 ACT-SYSTEM HARDWARE/SOFTWARE ACQUISITION AND TEST

Definition of the Demonstration ACT System, a task within the advanced technology element of this program (sec 3.4.3), will identify the ACT system elements that should be flight tested. It is probable that certain aspects of the risk–real or perceived–associated with implementation of ACT will be resolved only through ground and/or flight tests. It is proposed that, at this point in the program, test system specifications be developed along with a laboratory evaluation plan, a preliminary flight-test plan, and a plan for acquiring flightworthy critical system elements for test (fig. 6). Flight program strategy will be considered when selecting and acquiring system elements. Flight-test preliminary plans will include identification of a candidate airplane, if it is

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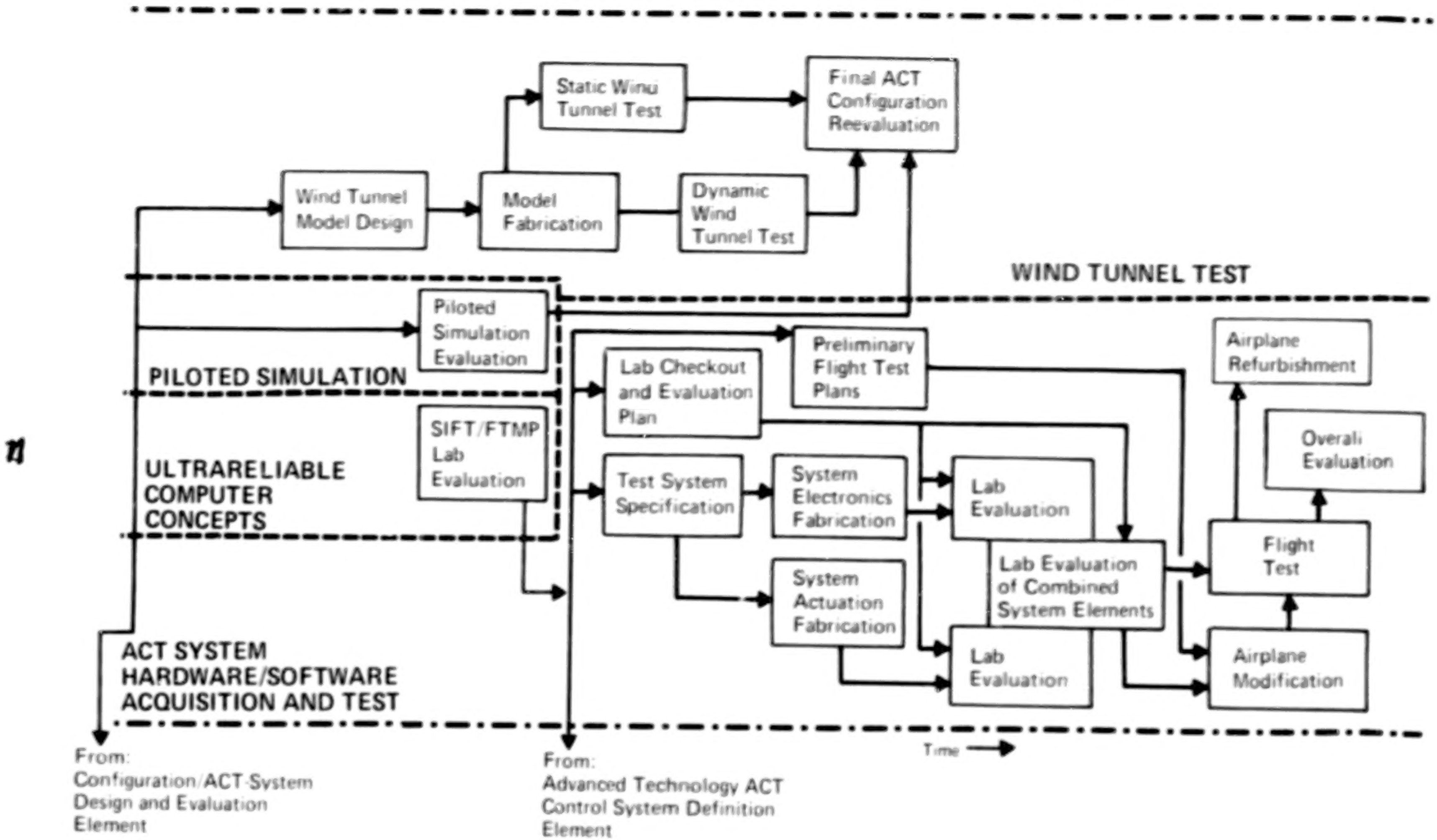

Figure 6. Test and Evaluation Element

to be other than a new airplane, and the specific types of testing to be undertaken. Finally, the airplane would be modified, flight tests conducted, and an overall evaluation completed. Following the flight test, the airplane would be refurbished to its initial state.

4.0 RECOMMENDED PROGRAM SCHEDULE

Figure 7 shows a program schedule for the phases and activities described in Section 3.0*. Although activities are categorized by Configuration/ACT–System Design and Evaluation, Advanced Technology ACT Control System, and Test and Evaluation, most activities are, in reality, continuous throughout the program plan. The interrelation and time phasing of the activities provide a basis for organizing near-term plans capable of meeting overall program plan goals, as well as budgetary and priority constraints or alternatives directed by periodic evaluation of results.

Design requirements and objectives are developed throughout the program, and at the end of each major phase they provide technical direction for succeeding program activities.

The ACT configuration is developed through a series of steps, starting from the initial ACT design that provides design integration method improvements and an assessment of the benefits of ACT, to the final ACT design sized to meet the Conventional Baseline Configuration mission.

Advanced technology ACT system work begins shortly after the start of the current technology system development and supports system selection for test and evaluation. The Test and Evaluation element of the recommended program begins soon after the definition of the Final ACT Configuration. As shown in Figure 7 the total program will require approximately 6 years.

* Since this document was initially released, significant parts of the recommended plan have been completed and documentation drafted or released as shown in Figure 7.

Notes:

- Shaded bars indicate completed technical tasks
- Circled numbers refer to completed documentation listed on next page

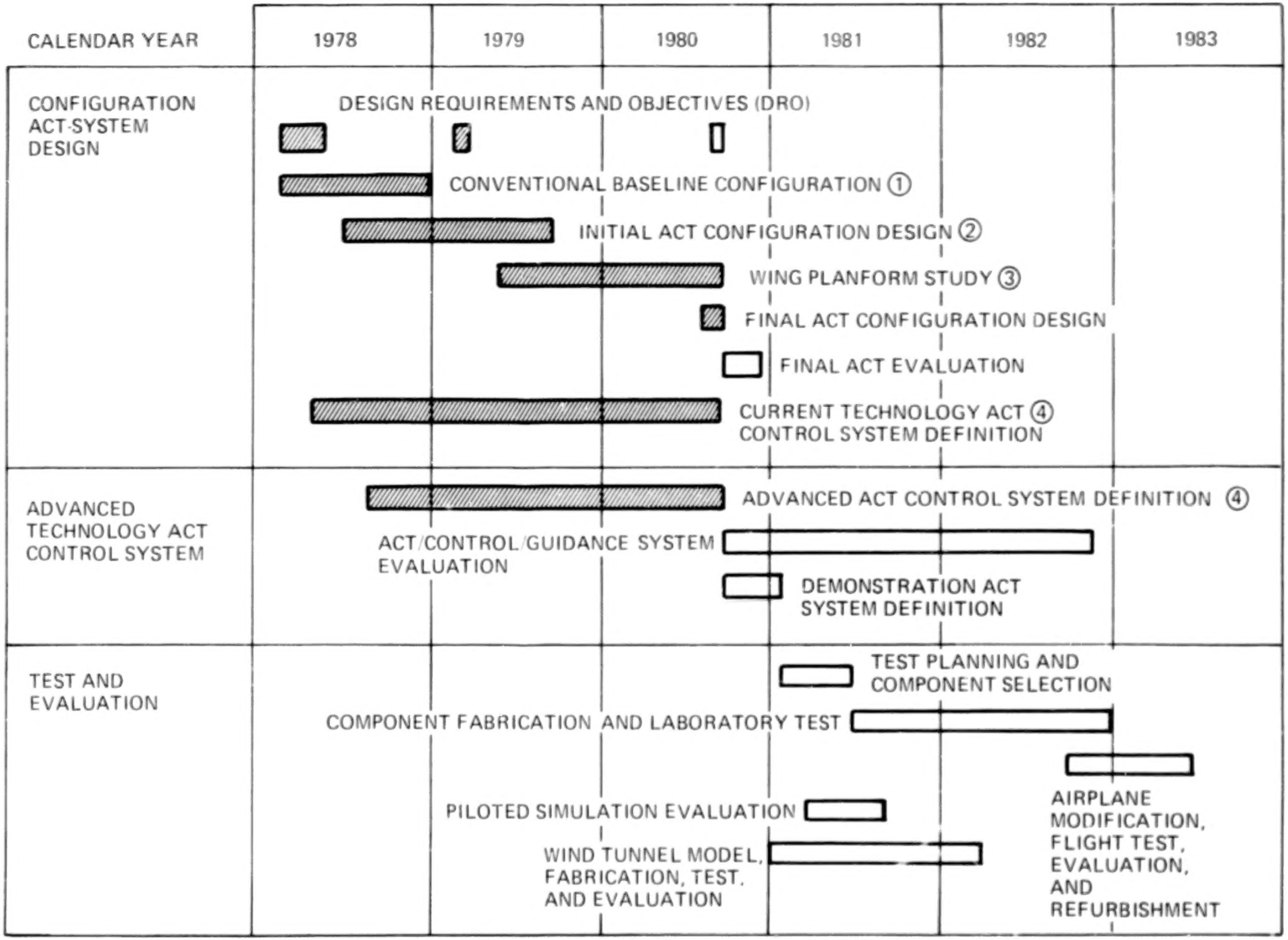

Figure 7. Recommended ACT Development Program Schedule

① *Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project—Conventional Baseline Configuration Study.* NASA CR-159248, Boeing Commercial Airplane Company, June 1980.

② *Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project—Initial ACT Configuration Design Study; Final Report.* NASA CR-159249, Boeing Commercial Airplane Company, 1980.

Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project—Initial ACT Configuration Design Study; Summary Report. NASA CR-3304, Boeing Commercial Airplane Company, 1980.

③ *Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project—Wing Planform Study; Final Report.* NASA CR- 165630 , Boeing Commercial Airplane Company, to be published in 1981.

Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project—Wing Planform Study; Summary Report. NASA CR-XXXX, Boeing Commercial Airplane Company, to be published in 1981.

④ *Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project—Current and Advanced ACT Control System Definition Study; Final Report—Volume I; Appendices—Volume II.* NASA CR- 165631 , Boeing Commercial Airplane Company, to be published in 1981.

Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project—Current and Advanced ACT Control System Definition Study; Summary Report. NASA CR-XXXX, Boeing Commercial Airplane Company, to be published in 1981.

Figure 7. Recommended ACT Development Program Schedule (Concluded)

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5.0 CONCLUSIONS AND RECOMMENDATIONS

Over the past decade, many theoretical analyses and several U. S. Air Force and NASA flight demonstration programs have addressed the potential benefit of active controls technology. Results of this work have been promising, but have stopped short of a definitive assessment of the benefit of active controls technology applied to a commercial transport. There is sufficient promise of significant benefit to justify a program that would address this assessment.

NASA/Boeing should immediately undertake the recommended ACT program outlined in Sections 3.0 and 4.0 of this document. This program will provide a credible assessment of a major application of Active Controls Technology to a commercial transport and will begin reduction of the perceived risk to a level commensurate with current commercial practice.

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APPENDIX A

ACTIVE CONTROLS TECHNOLOGY STATE OF THE ART

During the past decade, potential benefits of Active Controls Technology (ACT) have been shown by a large number of theoretical analyses and by several U. S. Air Force and/or NASA flight demonstration programs. Figure A-1 briefly summarizes results of most of these efforts.

Major Air Force experimental flight research programs involving load alleviation and fatigue damage rate reduction by structural mode control techniques were B-52 load alleviation and mode stabilization (LAMS) and the XB-70 gust alleviation and structural dynamic stability augmentation system (GASDSAS). Concurrently, an advanced stability augmentation system was developed and incorporated on the B-52G and H fleet to reduce fatigue damage rate during low-level, high-speed flight. The Air Force Control Configured Vehicle (CCV) research program has completed flight demonstration of four ACT concepts at selected flight conditions on a B-52 aircraft: ride control, flutter-mode control, maneuver-load control, and augmented stability. In addition, the compatibility of a LAMS system with these four concepts was demonstrated. Goals for each concept were successfully achieved, individually and collectively, during the program.

Other flight programs have incorporated limited ACT concepts in recently designed military and commercial aircraft. On the L-1011 transport, reduction of lateral gust loads by means of an advanced yaw damper resulted in a 20% reduction of limit design loads. A modal suppression augmentation system (MSAS), designed to improve passenger lateral ride qualities in the aft cabin, has been developed and certified for the 747. A ride control system was designed for the B-1 strategic bomber, using structural modal control techniques, to improve crew ride qualities during terrain-following missions. An active lift distribution control system (ALDCS) was designed for the C-5A airplane to reduce wing design limit maneuver and gust loads and wing fatigue damage rate. For the lightweight fighter, the F-16, relaxed inherent stability is integrated into the aircraft design to reduce drag and gross weight. The F-16 has a quadruply redundant analog fly-by-wire (FBW) control system. For the YC-14, the short takeoff and landing operation is dependent on the digital flight control system remaining operational.

Operational flexibility and reliability result from a triplex, digital, hybrid control system. The ACT functions incorporated in the L-1011, 747, and C-5A were "added-on" systems to improve flight characteristics, or to correct a design deficiency. However, they did not significantly affect the basic airplane configuration or design process.

The first serious commitment to include an ACT concept in a commercial transport occurred during the U.S. Supersonic Transport (SST) Program. The SST was configured with relaxed longitudinal static stability to achieve gains in range, payload, and noise. Experience gained at Boeing during the 1960s from development of fail-passive and fail-operational/fail-passive autoland systems provided the assurance that a suitable flight control system could be developed to meet SST safety and operational requirements.

The resultant SST longitudinal command and stability augmentation system providing basic airplane safety was fail-operational squared (fail-operate after second failure), using quadruply redundant sensors and analog electronic channels and actuators. A mechanical reversion backup mode was retained for unaugmented flight.

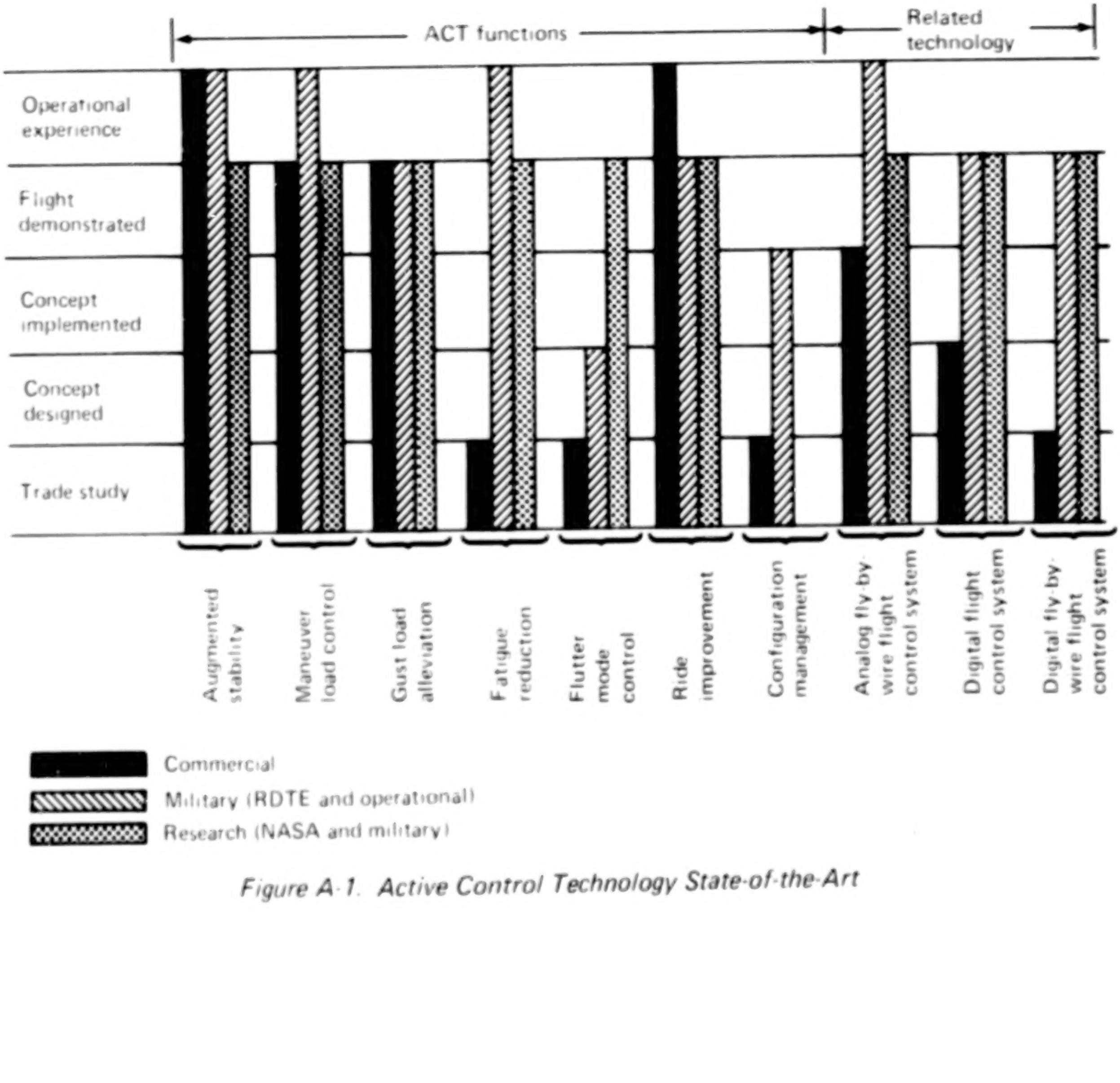


Figure A-1. Active Control Technology State-of-the-Art

Cancellation of the SST Program precluded thorough development and flight-test evaluation of the SST flight control system. Advanced technology items, including electronic display and control system components, were, however, Government funded for further development under the DOT/SST technology follow-on program (Contract DOT-FA72-WA-2893).

Most advanced FBW flight control systems have used analog implementation techniques. Research is underway to exploit the advantages of digital control, demonstrated in part by the Apollo space program. Recent extremely rapid progress in microcircuitry has made digital control hardware competitive with analog hardware in terms of costs, reliability, size, and weight. In addition, digital techniques offer significant advantages for advanced control laws, redundancy logic, and built-in testing functions. One of the first programs to study digital flight control implementation problems on aircraft is the NASA F-8 program, which successfully demonstrated a single-channel digital FBW primary flight control system with a triple-redundant analog backup system. Other digital control research programs, such as the digital avionics integrated system (DAIS), the SST follow-on technology, and the planned tactical aircraft digital system (TADS), are contributing to this technology base. Other Air Force programs are investigating the application of multiplexing techniques to flight control systems. Researchers also are studying fiber optics for providing signal transmissions immune to electromagnetic interference.

More recent NASA-sponsored programs include:

- DAST-ARW-II, an integrated design of a high aspect ratio research wing with an active controls system for flight tests on a BQM-34E/F drone vehicle; a methodology to conduct integrated ACT design will be developed and evaluated (Contract NAS1-14665 being conducted by Boeing-Wichita)

- The accelerated development and flight evaluation of load alleviation for an increased aspect ratio wing, and stability augmentation for reduced static stability (RSS) with a smaller horizontal tail on the Lockheed L-1011-500RE airplane (Contract NAS1-14690, Lockheed-California)

- The ACT concepts development on a derivative B-747 aircraft, a program that examines near-term non-flight-critical applications of maneuver-load control, gust-load alleviation and elastic modal suppression, wing tip extensions, and winglets (NAS1-14741, Boeing Commercial Airplane Company)

A currently ongoing independent research and development program is the 747 Wing Load Alleviation Demonstrator Program. This program involves modifying and flight testing a 747 that incorporates active wing-load alleviation with the outboard aileron.

An overall assessment of advanced flight controls technology over the past 15 years indicates that considerable progress has been achieved in various areas:

- Microcircuitry design and digital computer development to handle the large demands on control system capability with improved computational, design flexibility, reliability, and self-test capabilties

- Flight-test verification of the performance of individual active controls systems on existing airplanes, where the mathematical modeling is based on known airplane characteristics

- Demonstrating the potential benefit of improved integrated active controls systems applied to a controls configured vehicle design

Assessment of ACT also highlights various activities and programs needed to make ACT ready for acceptance by the airplane industry, the airlines, and certificating agencies.

Acceptance will occur when sufficient data are generated to demonstrate that the proposed ACT benefits can be met with reasonable risk (comparable to current technology) for an all-new design. The data must establish the validity of the ACT design tools, quantify the performance benefit, and show acceptable system reliability and maintainability characteristics. The airlines must be assured that they can keep the new systems operational with acceptable maintenance cost. Finally, the data must demonstrate that the development costs and cost of ownership of the flight vehicle are compatible with the commercial transport market requirements and that they warrant the financial risk that must be undertaken by the manufacturer and the operator. Conclusions from previous ACT studies indicate that greater benefit would result if the technology were applied as an integral part of the design from its initial conceptual phase. The final configuration would be determined by the use of all beneficial active controls functions. Maximum benefit for some ACT functions will result when the active controls function is a "flight-crucial system." A flight-crucial system is required when the "unaugmented" airplane does not meet certification and/or safety requirements, and thus cannot be operated with that system inoperative.

The ability to predict the aeroelastic and dynamic characteristics of a new airplane, with sufficient accuracy to design active controls that will meet the required system performance and reliability requirements, has not been demonstrated. Analytical tools for integrated aerodynamic/structural/control system analysis also need improvement. Complex software and hardware systems that meet safety, performance, and life-cycle cost requirements need to be developed and demonstrated. Hard trade-study data, to quantify the benefits of ACT, and design requirements and criteria need to be generated. The design benefits, ACT design integration methods, and hardware flight worthiness need to be validated through correlation of predicted characteristics with laboratory and flight test experiments.

The history of ACT suggests that incorporation of the full range of ACT in the commercial fleet will continue to be an evolutionary process. This process was initiated with introduction of individual ACT functions to solve a specific design problem or, more recently, to provide growth for an existing design. Acceptance of these systems is evidence that both manufacturers and operators are prepared to exploit the full range of the technology whenever ACT appears to be ready and profitable.

APPENDIX B

PROBABLE ACT AND REFERENCE AIRPLANE CONFIGURATIONS

One objective of this task was to define a probable active controls commercial transport configuration. Configuration definition required that consideration be given to how Active Controls Technology (ACT) can provide a beneficial impact upon a commercial airplane. The specific impact of ACT depends upon both the target mission (airplane design payload/range) and the type of configuration being considered (e.g., number of engines, placement of engines, empennage configuration). The following discussion treats the target mission selection and the assumptions and rationale leading to the probable configuration.

B.1 FLEET FUEL REQUIREMENTS

An objective of the NASA Energy Efficient Transport (EET) Program is to pursue technology developments that could lead to reductions in fuel requirements of commercial transports. Therefore, airplane fleet fuel use is one of the considerations in selecting the mission that this airplane must meet. Figure B-1 illustrates the annual fuel consumption of various domestic fleets. Information in this figure was taken from

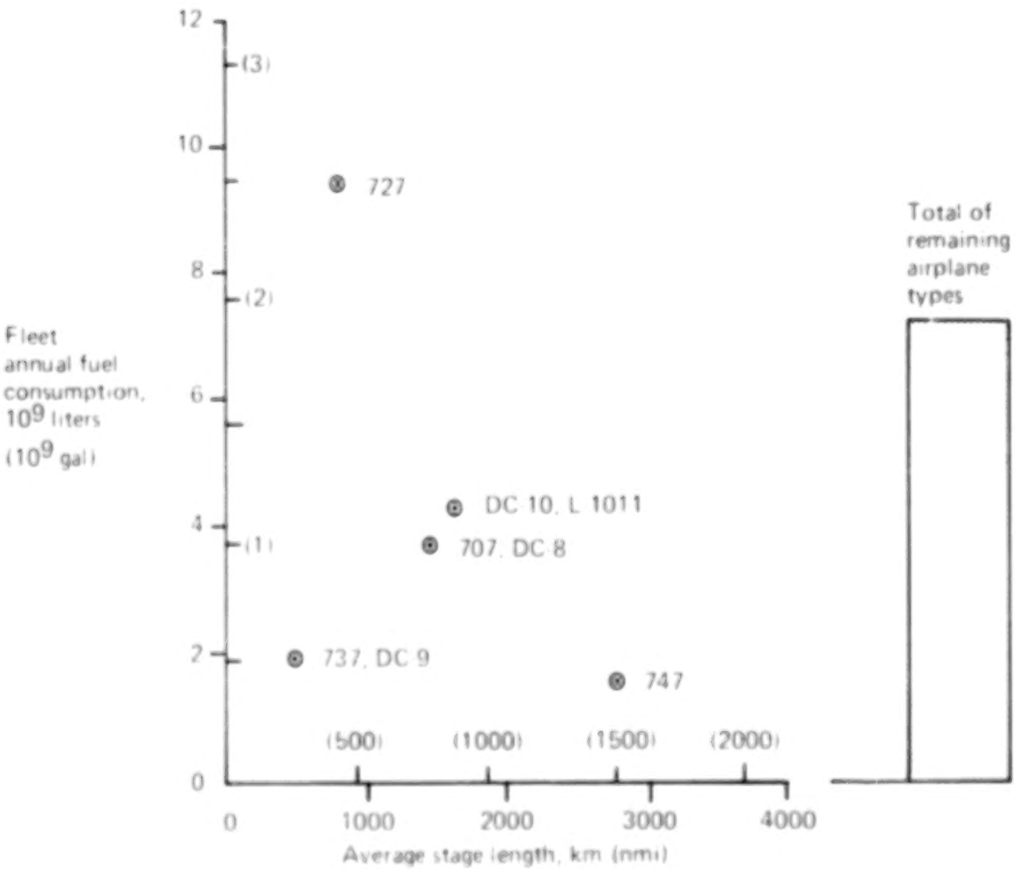


Figure B-1. Fuel Usage—Domestic Airline Fleet

the July 1977 Civil Aeronautics Board Aircraft Operating Cost and Performance Report. Note that the 727 fleet annually consumes almost 9½ billion liters (2½ billion gallons) of fuel operating over an average stage length of about 930 km (500 nmi). In the domestic airlines fleet, the 727 fleet used the most jet fuel because of the great number of 727 airplanes and the large number of flights. Stage length, as used in this discussion, refers to the distance between takeoff and landing. For example, a transcontinental flight with one or more stops would be described as having several stages.

B.2 TARGET MISSION

Figure B-2 illustrates the number of flights in each stage length, resulting in an average distance of approximately 930 km (500 nmi). Due principally to city-pair spacing, 65% of these flights occur over stage lengths of 930 km (500 nmi) or less. However, the ACT airplane designed to have maximum ultimate impact on this fuel use should not be designed to the 930 km (500 nmi) stage length. To provide airline flexibility, an airplane designed to service these routes should have a design range of from 2800 to 3700 km (1500 to 2000 nmi).

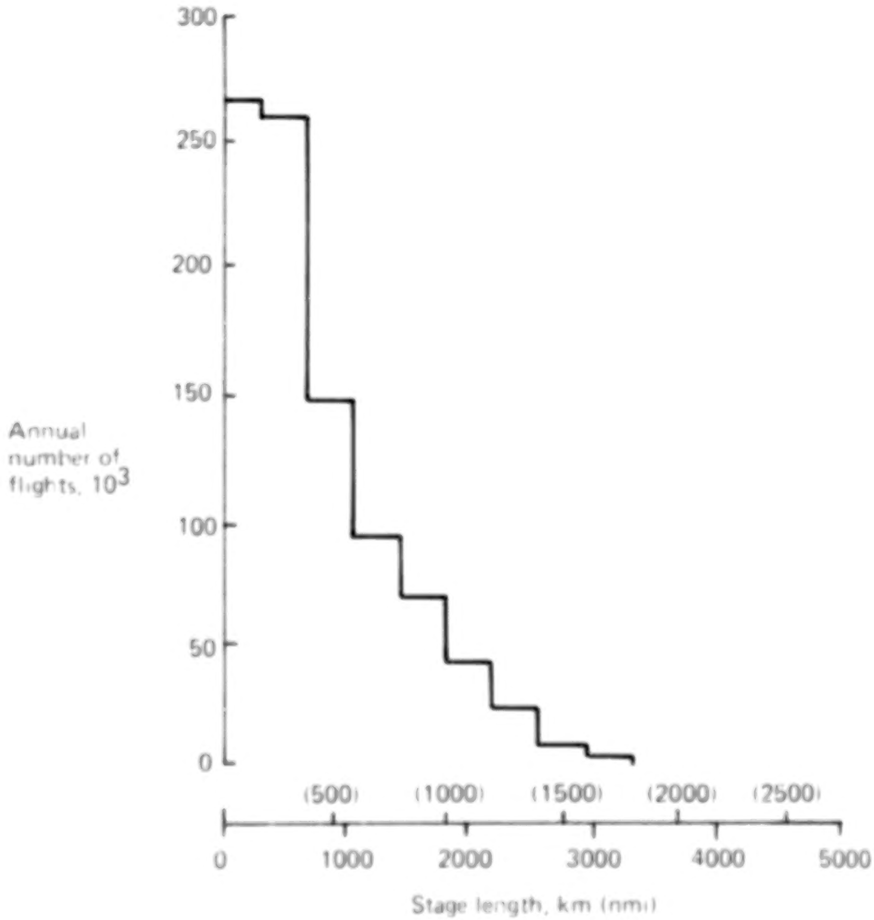


Figure B-2. Flight Stage Length Distribution – 727 Domestic Airline Fleet

For purposes of this discussion, the ACT airplane mission will be defined to be an 3300-to-3700 km (1800-to-2000 nmi) design range with 150 to 200 passengers. The ACT airplane configuration designed to meet this mission would have performance characteristics (payload, range, cruise speed) similar to those airplanes of the current transport fleet that consume the most jet fuel. Therefore, such an ACT airplane conceivably could have the greatest impact on fuel used in domestic airline operation if the existing airplanes were replaced by the ACT airplane.

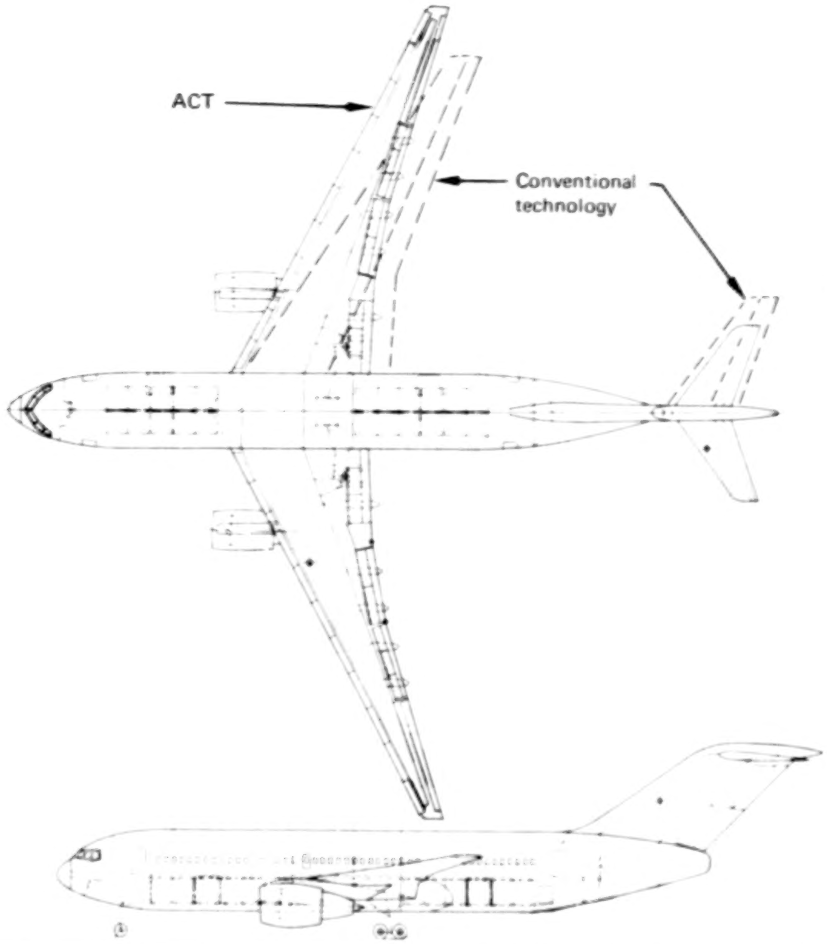
A recommended ACT program baseline (reference) airplane should be established and the improvement due to active controls be determined by comparing the performance and economics of the ACT airplane with those of the baseline airplane. The baseline airplane should be a modern commercial transport designed for the selected mission.

The following is a summary of the target airplane characteristics established for the ACT design. Note that the ACT airplane designed under these ground rules will meet the same mission as the reference airplane and use the same level of technology in all areas except ACT.

- Configuration
  - Passengers — 150 to 200
  - Engines — 2 or 3
- Design mission
  - Cruise Mach — 0.80
  - Range — 2800 to 3700 km (1500 to 2000 nmi)
  - Takeoff field length — 2440m (8000 ft) maximum
  - Approach speed — 250 km/h (135 kn)
  - Noise — Current commercial conventional transport practice
  - Flying qualities — Current commercial conventional transport practice
- Technology
  - The airplane technology (aerodynamic, structural, propulsion, etc.) to be consistent with current commercial conventional transport practice.

B.3 PROBABLE ACT AIRPLANE DESCRIPTION

A probable ACT airplane configuration (fig. B-3) has been developed to illustrate the type of configuration that may result from a major application of ACT. This configuration is assumed to meet the target mission (app A) through application of ACT to reduce the structural weight accompanying increased wing aspect ratio and reduced wing sweep. In addition it allows the empennage size to be reduced. The following text discusses the overall airplane configuration and assumptions associated with its sizing, the general control system arrangement and aerodynamic control surface ACT assignments, the specific ACT functions that have been assumed, and preliminary reliability requirement concepts reflecting both safety and dispatch.



Geometry	Wing	Vertical stabilizer	Horizontal stabilizer
Area, m^2 (ft^2)	247 (2656)	56 (601)	35 (376)
Aspect ratio, AR	12	0.67	4
Taper ratio, λ	0.30	0.70	0.4
Sweep C/4, deg	26	55	35
Tail vol coeff, v	–	0.088	0.662

Maximum takeoff weight, kg (lb): 113 310 (251 800)

Propulsion, N (lb): Three 109 000 (24 500) SLST JT10D-2 engines

Body cross section:

- Shape: Double lobe
- Maximum width, m (in): 5.03 (198)
- Maximum height, m (in): 5.22 (205.55)

Passenger accommodations:

	Passengers	Abreast	Pitch
First class	23	5	0.97m (38 in)
Tourist	178	7	0.86m (34 in)
Total	201		

Cargo and baggage, m^3 (ft^3): Eleven LD-1 or LD-3 type containers plus bulk

Figure B-3. Probable ACT Airplane

B.3.1 OVERALL AIRPLANE CONFIGURATION

The configuration was assumed to result from a design procedure that included ACT from the outset of the design process. However, to underscore the changes that active controls may bring about, various aspects of the overall airplane configuration are compared to a reference conventional configuration. This reference configuration (app B, sec. 2) is a preliminary design modern airplane, designed for the same target mission as the ACT configuration. The passenger and cargo payloads are identical, hence the two airplanes have identical bodies.

The presence of ACT was assumed to allow the designer greater freedom in selection of wing sweep and aspect ratio. For this target mission, 3430 km (1850 nmi) range, a cruise Mach number of 0.8, a wing quarterchord sweep of 26 deg, and an aspect ratio of 12 were selected. The wing thickness ratio was estimated to be 13.1% at the root and 8.3% at the tip to yield the desired cruise Mach number. The reference airplane has a wing sweep of 31.5 deg and an aspect ratio of 8.7. The assumption made for the ACT airplane is that ACT functions allow the wing to be fabricated for a lower weight penalty than possible without ACT functions.

Stability augmentation functions were assumed, allowing a more aft balance of the airplane and a reduction in tail area of about 40%. The tail area reduction also reduces the body loads and structure and results in both a lower drag and airplane weight. These changes in wing geometry and empennage size were estimated to reduce the fuel required for the target mission by about 10%. The resultant airplane is shown in Figure B-3. The figure also shows the referenced conventional technology airplane.

B.3.2 GENERAL CONTROL SYSTEM ARRANGEMENT

The philosophy of the ACT system implementation is to make it as transparent as possible from the pilot's point of view. The objective is to make the airplane appear to be a conventional (non-ACT airplane), as far as the flying qualities and general operation of the airplane are concerned, except in the presence of failures that require pilot action. The ACT system implementation will involve a summation of the ACT control commands and the pilot's commands, either through the airframe dynamics or specifically at control surfaces. At this time, the specific means of bringing these signals together is not described for each system, but will result from the design of an ACT airplane.

The discussion of the following control system elements is presented as though the airplane had already been designed, so that one approach to the active controls system design can be highlighted. Selected choices should not be construed to be final, but rather a general discussion based upon engineering judgment prior to the design.

Major components of all ACT systems are the sensors, computers, and servoactuators. These ACT elements interface with the aircraft flight control system to drive the power control unit (PCU) that operates the control surfaces. This interface takes one of two forms. Mechanically commanded PCU's receive inputs from secondary series servos that sum ACT and pilot commands. Electrically commanded PCUs directly sum the ACT and pilot commands. Crew interface with the system is through a mode control panel with failure warning displayed on the master warning panel. A system test capability is provided for maintainance. Automatic built-in test capability, initiated by the flight crew, verifies the operational status of the system for preflight checkout. The ACT general control system is multifunction and includes pitch-

augmented stability (PAS), maneuver-load control (MLC), gust-load alleviation (GLA), and flutter-mode control (FMC). Functions used by the ACT configuration are further described in Section 3.3, ACT Functions.

B.3.2.1 SENSORS

The general vehicle states associated with each of the ACT functions are acceleration, attitude rate, control position force or displacement, and airspeed. Multiredundant units are packaged to minimize signal variations arising from input axis alignment and calibration. The sensor units are capable of being stimulated to facilitate automatic checkout during ground tests. The sensor/computer interface employs analog prefiltering to prevent aliasing problems. Consideration is given to placement of the sensors, not only to accomplish the objective of their respective control functions, but also to provide common inputs to the multivariable control scheme, which is consistent with the system failure requirements.

B.3.2.2 COMPUTERS

The computer unit, which is the central element of the ACT system:

- Interfaces with external system components
- Conditions signal inputs, processes the input information, and transmits commands to control surface actuators
- Performs inflight failure monitoring, failure status annunciation, and system shutdown
- Performs preflight checkout to verify system operational integrity
- Provides a semiautomated maintenance test that does not require ground support equipment to identify a failed line-replaceable unit

The computer is software-partitioned to handle the various ACT functions. The number of system channels and processing architecture is determined by the reliability requirements for safety and dispatch. The nature of the tasks performed leads to selection of a digital computer, with emphasis on failure monitoring, control, and self-check capability. The nature of the control laws alone is not complex; however, machine speed is important in relation to the frequency bandwidth of control. Consideration of the advantages of hardware reliability and data management may lead to the selection of a hybrid (analog/digital) computation scheme.

B.3.2.3 ACTUATORS

Two basic actuation concepts are used for implementation of the multifunction ACT system. In the first concept, a secondary servomechanization scheme uses two identical force-summed series servos that are series-summed with the baseline mechanical control input to the existing surface PCU.

The dual-servo concept provides protection against hardover failures, by a hydraulic pressure-regulated detent located between the actuator piston and the output linkage. The detent mechanism also provides protection against oscillatory failures of significant magnitude. Both electrical and hydraulic multichannel redundancy is incorporated into the fly-by-wire (FBW) servoactuators to guarantee fail/operational capability.

Failure monitoring of the secondary servomechanism is accomplished by cross-channel comparison of actuator piston displacements sensed by linear variable differential transformers. When a failure is detected, the secondary servos are shut down by depressurizing the actuators and forcing the output linkage to neutral with the centering spring and detent. Normal mechanical input to the control surface PCU is not affected.

In the second concept, pilot inputs, autopilot commands, and all ACT control system functions are electronically integrated before being transmitted to multichannel FBW actuators.

Failure monitoring of the FBW concept is accomplished by continuous comparison of the redundant multichannel input commands. When an erroneous channel is discovered, it is immediately shut down. The PCU involved is operational after one failure and passive (nulled) after two failures. Use of PCU mathematical models in the ACT computers could be used to maintain the PCUs operational following two failures for a flight crucial system.

Hydraulic power for the secondary series servos, or the FBW servoactuators, is supplied by four independent 20 700-kPa (3000-psi) hydraulic systems. Demands of the ACT system will size the hydraulic pumps and distribution system, in contrast to conventional airplanes where secondary controls or landing gear systems are critical.

B.3.2.4 CREW INTERFACE/MAINTENANCE

Flight crew interface with the ACT system is via a mode control and annunciator panel and is limited to switching the system on/off and initiating preflight checkout. The checkout sequence verifies system operational integrity and indicates a go/no-go conclusion.

Reliable failure warning, following a system failure, is designed into the system to promptly alert the crew through the master warning system. The appropriate functional failure (e.g., loss of maneuver-load control) is indicated and any required pilot action identified. The failure monitoring system detects failures to the line-replaceable-unit level and, upon replacement of a faulty unit, the system is tested without the need for ground-based test equipment.

B.3.3 ACT FUNCTIONS

The ACT functions are grouped into airplane mode control and structural mode control. The airplane mode control tends to be low frequency and involves the traditional stability augmentation, whether pitch or lateral/directional degrees of freedom, and control of strength-impacting loads due to maneuver and gust. The high-frequency ACT functions include the control or attenuation of wing flutter, and the improvement of passenger and/or crew ride in either vertical or lateral degrees of freedom.

The following discussion illustrates a means of implementing various functions assumed for the configuration shown in Figure B-3. Specific implementation of these functions for a particular design can be determined only after careful consideration of the requirements, objectives, and benefits associated with each of the candidate ACT functions. While the following discussion is presented in present tense, it is postulated for purposes of discussion only.

B.3.3.1 STABILITY AUGMENTATION

The inclusion of augmented stability functions allows relaxation of the inherent aircraft static or dynamic stability. This primarily benefits the longitudinal axis, with related reduction in the horizontal stabilizer surface area. The conventional yaw damper function is an example of augmented stability applied to the lateral/directional axes to increase the Dutch-roll mode damping, with a resulting beneficial impact on the configuration.

Pitch augmented stability is achieved by commanding the elevator control surfaces in response to vertical acceleration feedback at the center of gravity. The vertical acceleration signal is shaped to augment the short-period mode. Command augmentation shapes the pilot column inputs to retrieve basic aircraft handling qualities. Control feel may be programmed with airspeed. Servoactuator commands are scheduled to command the outer elevator segment in low-speed flight, while the inner segment is driven over the full-speed envelope.

Lateral/directional augmented stability is achieved by commanding rudder control surfaces in response to yaw rate at the center of gravity, with command augmentation from pilot rudder pedal position to retrieve basic handling qualities. Yaw rate feedback is shaped to attenuate and to minimize turn interference. Both upper- and lower-rudder surfaces may be used to control Dutch-roll damping mode in cruise.

The stability augmentation functions selected, and their degree of criticality or airplane dependence, will result directly from the performance benefits that are possible. Experience with more conventional airplane designs, such as the 727, suggests that the resulting ACT airplane will be dependent upon satisfactorily functioning stability augmentation over significant parts of the flight envelope. For example, Dutch-roll or lateral/directional augmentation probably will be necessary at cruise conditions to meet the required damping levels. However, both logitudinal and lateral/directional characteristics of the airplane may lead to a satisfactory "inner" flight envelope, where the augmentation may not be mandatory. Specific details of such criticality will be determined during the final design.

B.3.3.2 MANEUVER-LOAD CONTROL

Maneuver-load control reduces wing vertical bending moments during maneuvering flight. The assumed system senses airplane vertical acceleration and pitch rate and conditions this information to modulate outboard and/or inboard control surfaces to reshape the wing span load distribution by moving the center of pressure inboard. MLC-induced pitch trim disturbance is compensated by input command to the elevator. Airspeed gain scheduling is necessary to compensate for outboard control aeroelastic effects at high speed, because MLC operates over the full flight regime. The MLC system implementation is such that airplane safety is at least equal to that of current commercial transports, including considerations of probability of MLC systems failure.

B.3.3.3 GUST-LOAD ALLEVIATION

Gust-load alleviation reduces the structural loading that results when the airplane penetrates vertical or lateral gusts. The strategy of the system is to control the gust load onset through deflections of the wing controls and to pitch the airplane into the gust through commands to the elevator.

Control of gust-induced lateral/directional rigid body motion is achieved by using a sideslip vane to detect lateral gusts; subtracting airplane motion derived from lateral acceleration, yaw rate, and roll attitude; and filtering the resultant signal to command rudder control surfaces to reduce the airplane tendency to turn into the gust. A system that only improves Dutch-roll damping may be satisfactory for some configurations.

The GLA systems discussed here are principally designed to reduce structural loading at rigid-body frequencies. It is recognized that these systems impact dynamic loading from low-frequency structural loads and airplane handling qualities. Consequently, the complete active controls system must be tuned to eliminate any adverse effects. Airplane safety considerations for the GLA system are the same as for the MLC system.

B.3.3.4 FLUTTER-MODE CONTROL

Flutter-mode control increases the aircraft flutter placard speed by actively suppressing (increasing the damping of) selected flutter mode(s). Flutter criteria have been developed to ensure airplane safety compatible with current commercial transports.

Two wing trailing-edge surfaces and associated control loops provide the required redundancy. Each surface is capable of individually meeting system performance requirements. Vertical accelerations from selected wing locations near the associated wing trailing-edge surfaces are used for command. The FMC system increases modal damping at the flutter frequency and is compatible with other control function loops. As with the MLC and GLA systems, using FMC in an airplane does not compromise safety.

B.3.3.5 FATIGUE REDUCTION SYSTEMS

Elements of the GLA system, and other ACT systems where appropriate, are tuned to minimize fatigue damage rates due to flight in turbulent and/or gusty air. Fatigue reduction is critical to continued flight in a manner different from that described for the previous systems. In the presence of a total failure, there is not an immediate threat to the airplane. Rather, failure leads to increased damage rate, a reduction in airplane life, or a requirement for an early maintenance action.

B.3.3.6 RIDE IMPROVEMENT SYSTEM

The ACT airplane must have ride qualities comparable to current commercial transports of similar size. The reduced wing sweep and increased aspect ratio lead to the necessity for a ride improvement system. Ride is improved by tailoring the gust load system at the lower frequency structural modes to reduce the energy perceived by crew and passengers.

The ride system is unique among the ACT functions; if the ride system fails, the only immediate problem is passenger discomfort.

B.3.3.7 ACT FUNCTION INTERDEPENDENCE

The ACT sensor elements for acceleration and velocity (angular rate) are strategically located in the wing and fuselage area to satisfy as many control functions as possible, consistent with adequate design control margins. Failure implications of this commonality must be assessed. Controllability of several functions, in themselves relatively simple, poses a concern where all are functioning simultaneously within a small-frequency bandwidth. Careful filtering and control algorithm selection are required to minimize function interdependence.

B.3.4 RELIABILITY REQUIREMENTS

The combined requirements of safety, reliability, and system availability (dispatch) determined from the aircraft mission requirements determine the degree of redundancy required for the system elements; e.g., sensors, computers, and actuators. Different redundancy levels are required in the various subsystem elements to meet an economically justifiable and safe system. Different redundancy levels increase interface complexity. System architecture must be developed to handle the multilevel redundant functions.

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16. Abstract

This report briefly reviews the state of the art of Active Controls Technology (ACT) and outlines a recommended ACT development program plan. The objectives of the recommended plan are to conduct a credible assessment of the performance benefits and cost of ownership of an integrated application of ACT to civil transport aircraft, identify the risk and identify and conduct selected laboratory and/or flight experiments designed to reduce the technical risks to a commercially acceptable level.

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